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Hydrogeology of the Gradole Spring Drainage Area in Central Istria

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Key words: Hydrogeology, Karst, Spring, Drainage area, Surface watershed, Underground watershed, Central Istria, Western Croatia.

Abstract

The delimitation of a drainage area together with the accurate estimation of it's surface area represents an important problem in dealing with karst springs. Water gushing from the fractured karst identifies the Gradole spring as a typical karst well of the rising type. The spring never runs dry, the ratio of minimal and maximal discharge being 1:15 to 1:20 or more. The surface of the drainage area and its spatial distribution have been defined on the basis of geological data; tectonics, morphology, photo-geological interpretation, hydrogeological characteristics of the rocks, the karst morphology (sinkholes, pits) and underground water tracing data. The drainage area is predominantly composed of carbonate rocks, mainly limestone, but there is also a lesser flysch component - marls and sandstones. The karst area is without any surface waterflows, in contrast to the flysch area where a hydrographic network of intermittent surface streams is developed. There are no real barriers to underground flow within the carbonate rocks. Nevertheless, the direction of flow is influenced by structural elements, the position of layers, the appearance of rocks - thin layers, shows of some less permeable rocks - dolomites, fissured and marly limestones. The confirmation of an underground connection of Čiže swallow hole with the Gradole spring shows the possibility of supplementing low waters through the swallow holes from Butoniga accumulation lake.

1. INTRODUCTION

The Gradole spring is situated some 9.5 km from the mouth of the river Mirna (Fig. 1). The spring lies on the southern side on the edge of the river valley.

Hydrogeological exploration in Istria started at the end of 19th Century. The first discharge data for the Gradole spring are for the period of September-November 1913. Water-level measurement of this spring began in 1956. The first modern hydrogeological exploration in the area was done by MAGDALENIĆ & FRITZ (1959[1]), as a pilot project for the hydrogeological map of Croatia. Extensive geological-spelaeological exploration was carried between 1966-1968 by BOŽIČEVIĆ (1966[2]), BOŽIČEVIĆ & CUKOR (1967[3]) and BOŽIČEVIĆ (1968[4]). The Gradole spring is described in detail in the works of TOMAŠIĆ (1962[5]) and GULIĆ (1973), and the geology of the surrounding area is described in the reports of HAČEK & HANICH (1979[6]). Potable water from the Gradole spring was first distributed in 1973, and today, in summer, more than 1000 l/s is being abstracted.

The drainage area of the spring is predominantly composed of carbonate rocks, mainly limestone, with a lesser flysch component - marls and sandstone. Geomorphologically, the drainage area represents a karst plateau with an average altitude of approximately 330 m. Determination and interpretation of the drainage area is based on geological, structural, morphological and hydrogeological data and data obtained by tracing of underground waters both internal and external. The surface of drainage area was confirmed by hydrological parameters.

The basic geological data-set is to be found on two sheets of the General Geologic Map - OGK (Scale 1:100,000) - sheets Trst and Rovinj (PLENIČAR et al., 1969a, b).

2. GEOLOGY

2.1. LITHOSTRATIGRAPHIC REVIEW

The Gradole spring drainage area is composed of Cretaceous, Palaeogene and Quaternary deposits. Within the Cretaceous deposits, carbonate rocks; (limestones and dolomites) are predominant. Palaeogene sediments are mostly composed of clastics (marls and sandstones) with subordinate limestone. These strata are in part locally covered with Quaternary sediments of alluvial deposits and terra rossa (OGK, sheet Rovinj and Trst, Fig. 2).

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[1] MAGDALENIĆ, A. & FRITZ, F. (1959): Ogledna hidrogeološka karta Istre. List Rovinj 1:50 000.- Unpubl. tech. report, Institute of Geology, Zagreb.

[2] BOŽIČEVIĆ, S. (1966): Speleološka istraživanja područja južno od doline Mirne I i II.- Unpubl. tech. report, Institute of Geology, Zagreb.

[3] BOŽIČEVIĆ, S. & CUKOR, V. (1967): Hidrogeološka i speleološka istraživanja područja južno od doline Mirne.- Unpubl. tech. report, Institute of Geology, Zagreb.

[4] BOŽIČEVIĆ, S. (1968): Speleološka istraživanja izmedu ponora Čiže i vrela Gradole.- Unpubl. tech. report, Institute of Geology, Zagreb.

[5] TOMAŠIĆ, I. (1962): Ispitivanje izvora Gradole u dolini Mirne.- Unpubl. tech. report, OVP Rijeka.

[6] HAČEK, M. & HANICH, M. (1979): Izvještaj o rezultatima regionalnih hidrogeoloških istražnih radova sjevernih i centralnih dijelova Istre.- Unpubl. tech. report, Industroprojekt, Zagreb.

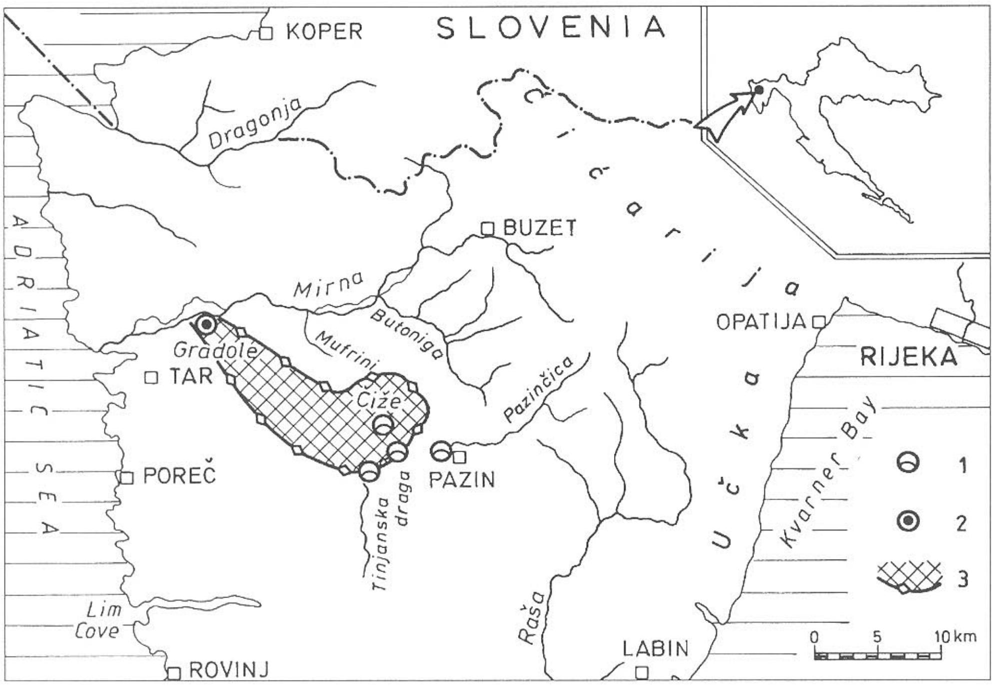


Fig. 1 Location map of the Gradole spring drainage area. Legend: 1) swallow hole; 2) spring; 3) Gradole spring drainage area.

2.1.1. Carbonate deposits

The oldest carbonate deposits are of Lower Cretaceous age (K$_1$). They include Barremian-Aptian layers in the SW and Albian layers in the central part of the study area. Barremian-Aptian layers are composed of either compact or powdery limestones. Beds are usually 50 - 100 cm thick, but can commonly reach to 2 m in thickness. Intercalations of sucrosic dolomite and thin-bedded limestones are occasionally found within the limestones, especially around Bokić, NW of Višnjan and SW of Kaštelir. In the area of Žužići and Višnjan there are intercalations of marly limestones between 5 and 20 cm thick, sometimes accompanied by thin beds of limestone breccia. Lithologically, the Albian deposits are similar to the Barremian-Aptian carbonates. They are mostly thin-bedded limestones (bed thickness between 20 and 40 cm). In the area of Kaštelir, bedding is thicker and there are sporadic interbeds of coarse-grained limestone breccias and marls. Dolomitic intercalations are also frequent.

The Upper Cretaceous (K$_2$) deposits are composed of thin-bedded limestones (average thickness of 20 - 50 cm). To the W of Vižinada, the limestones more thickly bedded (1 to 2 m), and are partly interbedded with thin dolomites.

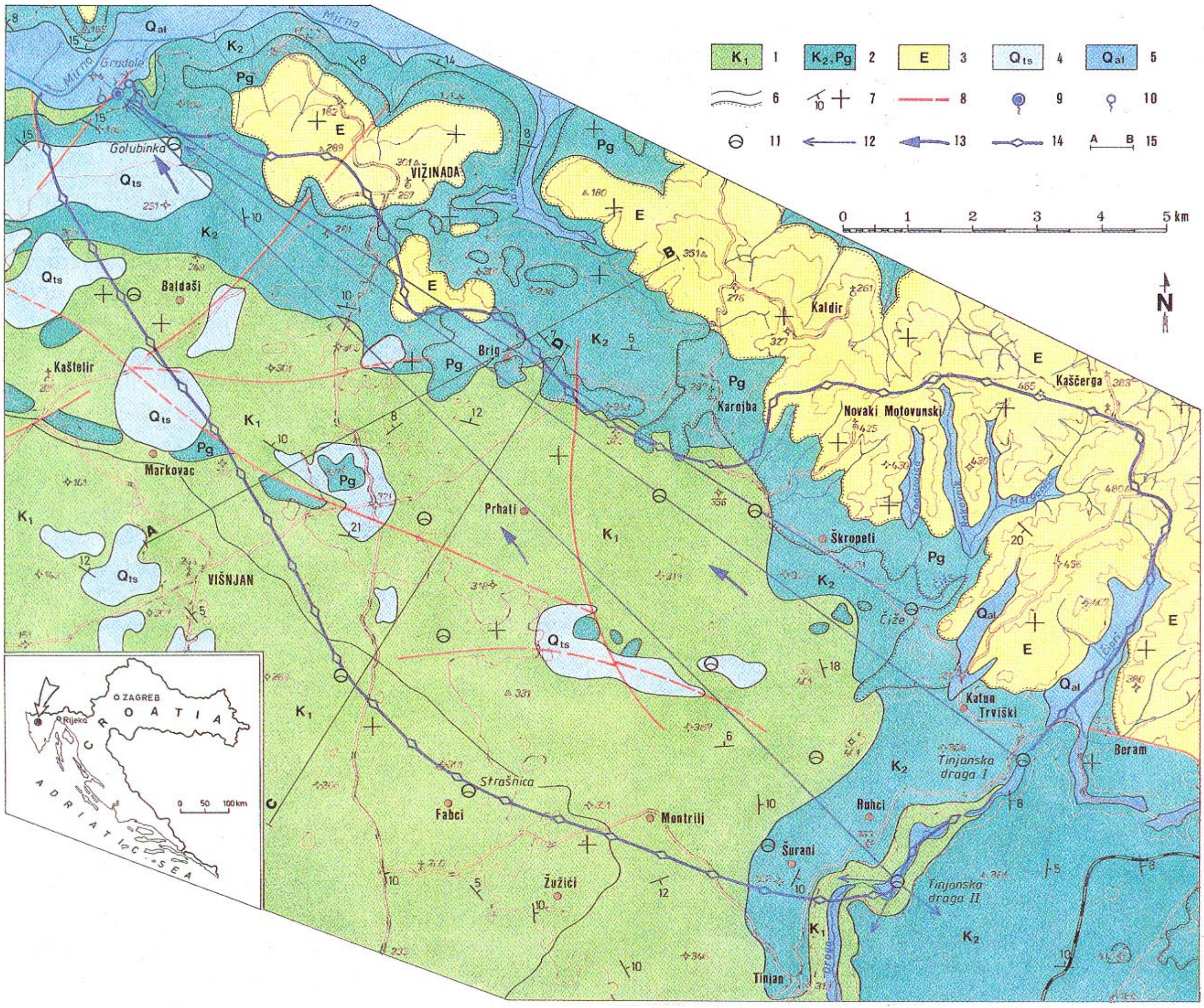
The Palaeogene deposits (Pg) are transgressive over the Upper Cretaceous, and are confined to the area of the Pazin basin. Emersion between the Cretaceous and Palaeogene is marked by the formation of bauxite deposits. All the carbonate Palaeogene deposits are shown collectively on hydrogeological map, although on OGK Miliolitic limestones (Pc,E$_1$), and Alveolina and Nummulite limestones (E$_{1,2}$) are differentiated. Miliolitic limestones are mostly found in the base of Foraminiferal limestones. Their thickness never exceeds 20 m, and they are usually thinner. The contact between Miliolitic and Alveolina limestones is gradual. The Alveolina limestones do not exceed 30 m in thickness. The Nummulite limestones occur in the same areas as the Alveolina limestones and there is a gradual contact between them. The upper part of the Nummulite limestones is usually breccia-like, but these rocks are generally more homogeneous and compact than the Alveolina limestones. Their thickness doesn't exceed 30 m.

2.1.2. Palaeogene clastic deposits - flysch (E)

Thick flysch deposits comprise the whole of the Buzet basin. They were deposited over different members of older sediments ranging from the Cretaceous to transitional layers with crustacea and globigerinidae. These deposits are characterized by their variable lithology,

Fig. 2 Hydrogeological map of the Gradole spring drainage area. Legend: 1) interbedded limestones and dolomites, marly limestones and dolomitic-lime breccias (less permeable in part); 2) limestones (very permeable); 3) flysch - marls and sandstones (impermeable deposits); 4) terra rossa (semipermeable); 5) sands, gravels and clays (variations of vertical and lateral permeability); 6) geological boundary, normal and erosional; 7) position of layer; 8) normal fault, indicated; 9) strong karst spring; 10) karst spring; 11) swallow hole/pit; 12) proved underground connection; 13) general direction of ground water movement; 14) borders of drainage area; 15) location of cross-sections on Fig. 3.

Fig. 3 Hydrogeological cross-sections. Legend: 1) thick layered limestones with interbeds of limestone breccias, marls, marly limestones and dolomites - less permeable; 2) Alveolina and Nummulite limestones (Pg) and thick layered limestones (K$_2$) - permeable; 3) Flysch - marls and sandstones (E) - impermeable; 4) geological boundary, normal and erosional; 5) fault; 6) watershed.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Mirna
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VIŠNJAN
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Karojba
Prhati
Kaldir
Novaki Motovunski
Kašćerga
Škropeti
Čiže
Katun Trviški
Beram
Tinjanska draga I
Ruhci
Šurani
Tinjanska draga II
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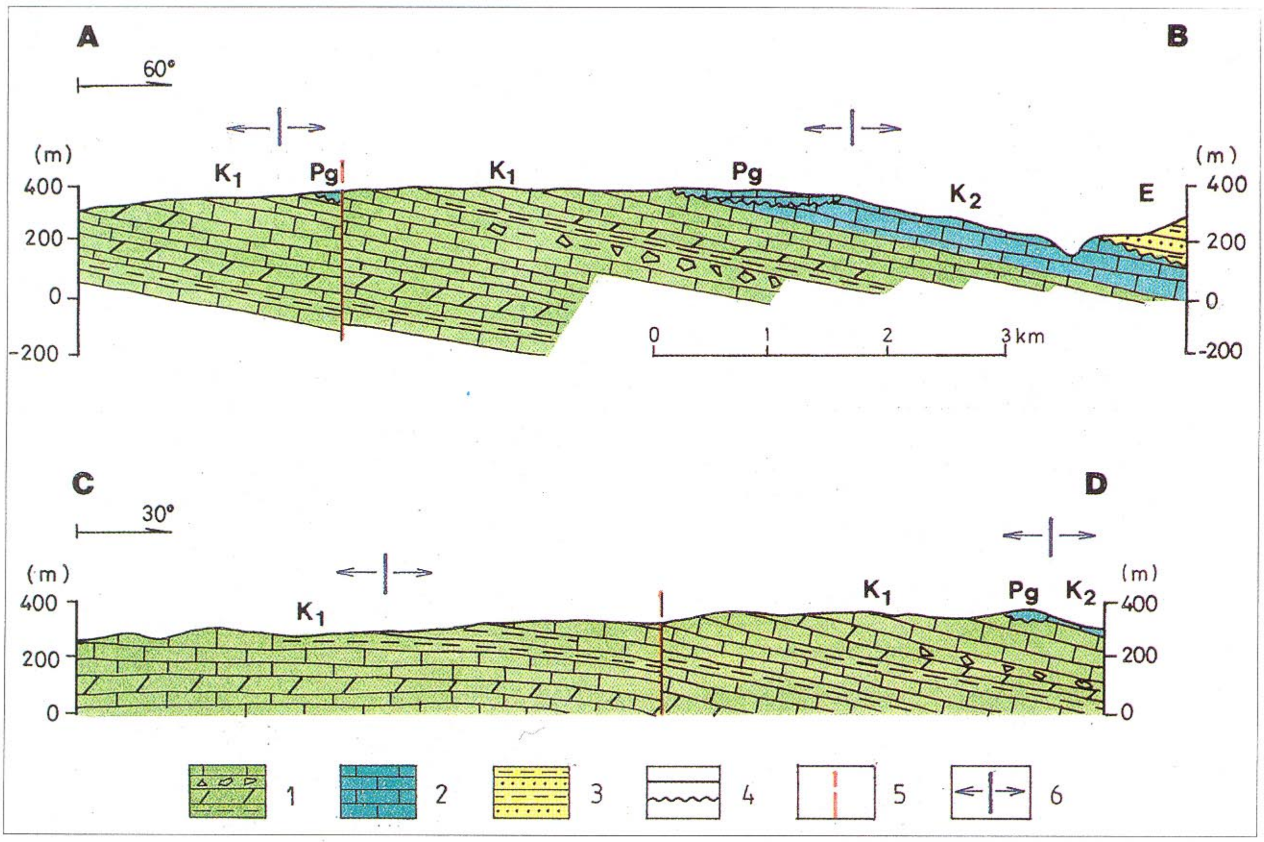
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particularly the interchanging of coarse- and fine-grained clastic sediments; sandstones and marls; and subordinate breccias, conglomerates and marly limestones. The dominant member of the Palaeogene deposits are marls.

2.1.3. Quaternary sediments (Q)

There are two genetic types of quaternary sediments - terra rossa and alluvial deposits. Terra rossa (Q_{ts}), occurs over the Cretaceous deposits, mainly as an incomplete cover of varying thickness (mostly between 0.5 and 1 m). Locally, terra rossa deposits occur, where the sediment can be more than 20 m thick, especially terra rossa infills broad depressions within the karst relief.

The Mirna river valley and the valleys of some of the larger streams in the clastic area of the Pazin Palaeogene basin (eg. Topolovica, Rakovnik, Marganica, Krvar, Čipri) are mostly filled with Quaternary alluvial beds (Q_{al}). These are mostly composed of clay and silt, and to a lesser extent sand and gravel, which are locally up to 10 m thick.

2.2. TECTONICS

The surroundings of the Gradole spring drainage area have a structural fabric formed by two tectonic units: West Istria Jurassic-Cretaceous anticline and the Pazin Palaeogene basin. The core of the anticline in the SW part of Istria is composed of thick-bedded Jurassic limestones, overlain by Lower Cretaceous deposits, mostly limestones. These deposits are gently folded. Although the anticline plunges towards the NE, it's contours are still observable through the Palaeogene deposits. The principal characteristics of these tectonic units are the very gently inclined strata (most frequently dipping at less than 12°) and marked radial tectonics: normal vertical and subvertical faults and fracture systems (Fig. 3). Classification of the faults and accompanying fracture systems of the area, according to the strike and frequency of appearance, was made on the basis of photogeological analysis. There are three main groups based on strike direction: those with strikes between NW-SE and WNW-ESE; strikes between NE-SW and NNE-SSW; and systems with predominantly E-W strike.

Fault systems striking NW-SE to NNW-ESE are approximately parallel to the axis of the Buzet-Pazin flysch basin and are therefore identified as the oldest. This is confirmed by the numerous bauxite deposits in the area, which are connected to the karstification along the fault systems (GULIĆ & ROGLIĆ, 1980[7]). This fault system is bisected by a fault system striking NW-SE.

Tectonic activity along fault systems striking NW-SE and NE-SW conditioned the downthrowing of rock masses in both the early SW - NE direction and later in a NW direction, towards Mirna river valley (PLENIČAR et al., 1973). The downthrowing of rock masses along faults of both these systems created complicated structural relationship that have a major influence on the underground water flow towards the Mirna river valley (especially in the zone marked by Čiže - Škropeti - Brig - Gradole), thus conditioning the hydrogeological connections of the area.

The southwestern part of the Pazin Palaeogene basin was formed by lowering of the NE section of the Jurassic-Cretaceous anticline during the Istrian-Dalmatian orogenic phase. The basin extends from Kaldire to the SE in the direction of Pazin and towards Vižinada in the NW, and is entirely covered by flysch deposits. Deepening of the Palaeogene basin is marked by faults along it's SW edge. Vertical faults are found in the vicinity of Vižinada and Beram, having displacements of approximately 150 m, and are observable on the surface. The flysch layers are mostly horizontal with minor local diversions close to the southwestern edge of the basin. This fact confirms the transgressive character of the flysch with a pronounced disconformity between the flysch and the older deposits.

3. HYDROGEOLOGY

3.1. KARSTIFICATION

The Gradole spring drainage area consists of rocks with different hydrogeological characteristics. One group is represented by carbonate rocks - mostly limestones and rarely dolomites and breccias, and a second by clastic flysch deposits - marls and sandstones with a dominant marly component.

In morphological terms, the carbonate rocks belong to a levelled limestone "plateau". They differ in age, lithological composition, bedding, structural-tectonic setting and by degree of tectonization. The flysch deposits represent another morphological unit, forming a hummocky area.

The average altitude of the carbonate plateau is approximately 330 m. The uniform morphology is disturbed by a microrelief expressed as many regularly shaped mounds 40-50 m higher than the surrounding terrain. The concave land-forms are even more pronounced; numerous sinkholes with dimensions varying from 10 - >100 m diameter. Their depths are also variable, from a few metres to several tens of metres. The number of sinkholes per square kilometer also varies, and is one of the quantitative indicators of the intensity of karstification. The numerous bauxite - filled depressions (between 10 and 90 per km^2) can be added to this number. Around 10,000 bauxite deposits have been found in Istria, with an average of 1,000 t of bauxite per deposit (ŠINKOVEC, 1973).

[7] GULIĆ, I. & ROGLIĆ, J. (1980): Kompleksni istraživački radovi u svrhu definiranja kvantiteta i kvaliteta voda krških izvora: Rakonek, Gradole, Sv. Ivan. Studija područja sanitarne tehnike.- Unpubl. tech. report, Faculty of Civil Engineering, Zagreb.

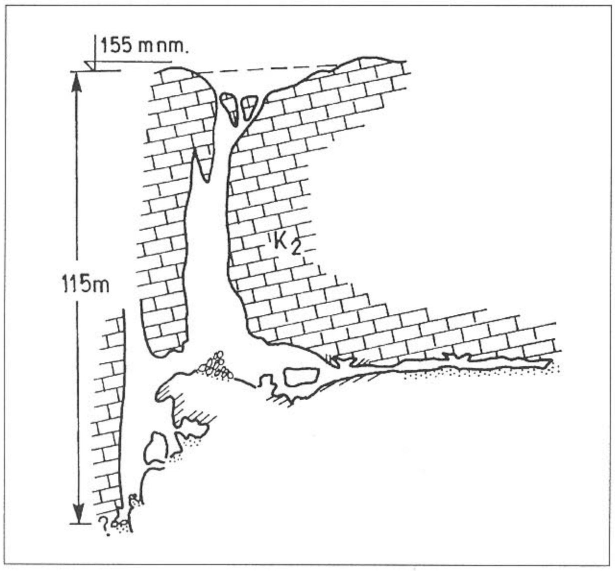

Fig. 4 Golubinka pit (after BOŽIČEVIĆ, 1985).

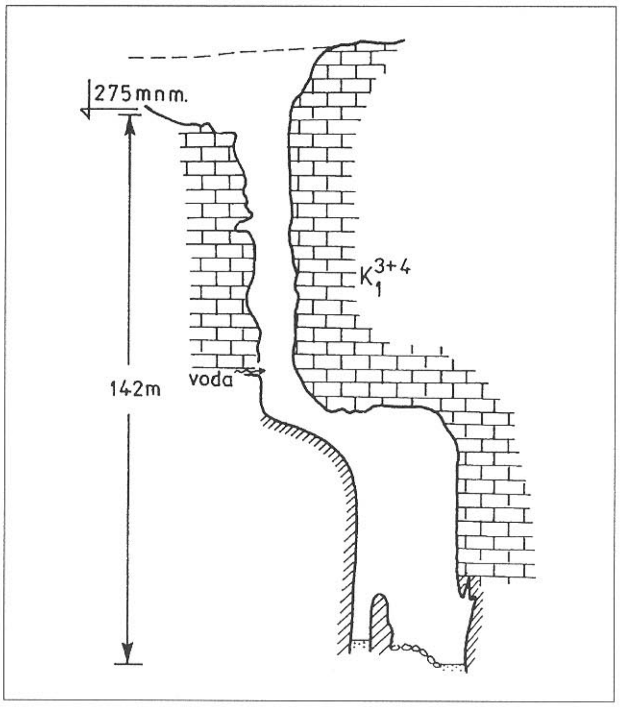

Fig. 5 Strašnica pit (after BOŽIČEVIĆ, 1985).

Spelaeological features, including caves, pits and swallow holes occur. They are defined by dimension and hydrogeological function, and detailed data can be found in the work of BOŽIČEVIĆ (1968[4], 1985). The number of spelaeological features varies between 1-10/km^2 and more than 100 have been registered. The majority of pits are 10-60 m deep, although some of them exceed 100m - for instance Golubinka pit (Fig. 4) and Strašnica pit (Fig. 5).

The spelaeological cross-section from Čiže swallow hole to Gradole spring shows that no such feature (except the Čiže swallow hole) reaches the level of underground water, and neither have surface water inflow. Spelaeological phenomena with steady or intermittent inflow or sinking of surface water are rare, but include the swallow holes in Beramska Vala and in the Drage valley, as well as the swallow hole area of Čiže.

Strong tectonic deformation, numerous faults and fractures, as well as sinkholes and pits make carbonate deposits very permeable. The rainfall of the area, which is unevenly distributed throughout the year, averages between 1,046 and 1,120 mm. It mostly infiltrates to the subsurface and to a lesser extent is evaporated. Besides the intensive infiltration of rainfall, carbonate deposits enable the infiltration of waters discharging from the flysch area in the form of brooks or torrents.

The anticlinal structure of the "Istria plate" and the zonal distribution of Jurassic and Cretaceous deposits (gently inclined towards the central part of the Gradole spring drainage area) are important to the flow of underground waters, especially in the season of low waters (BABIĆ et al., 1968). This is augmented by shows of dolomites, platy and fissured limestones, as well as shows of marly limestones within the Lower Cretaceous carbonate rocks. The major direction of underground water flow is SE-NW, towards the Mirna river, and coincides with the strike of some structures and major fault systems.

The case of Čiže swallow hole is characteristic. While surface waters of the drainage area flow from N-S, the underground waters in the limestones change the direction of flow towards the NW, parallel with the contact between the flysch and carbonate rocks.

Within the carbonate rocks, zones of greater and lesser permeability can be defined, are these rocks have therefore been hydrogeologically classified into two groups. The differences between the two groups are subtle. The group of very permeable rocks consists of the Upper Cretaceous bedded and boulder limestones and Palaeogene limestones. Lower Cretaceous deposits belong to the group of less permeable rocks, together with limestones and dolomites, platy and fissured limestones and interbedded marls.

Both Upper Cretaceous and Lower Cretaceous carbonate deposits are karstified and permeable close to the surface. This is obvious because of the numerous sinkholes, photogeologically defined faults and fractures, and mostly because of the lack of surface waterflows in the area of carbonate rocks. The only registered surficial waters are bigger and smaller pools which seasonally dry up. The hydrogeological function of the less permeable rocks becomes apparent in the subsurface, in the sense of directing the flow of underground waters in a specific direction.

It is a fact that the outflow of groundwater is concentrated in the Gradole spring, on the edge of the Mirna river valley. There are no larger springs from the Gradole spring down to the mouth of the river Mirna or in the coastal area between Tar and Limski kanal (Lim Cove). The coastal springs are usually brackish and they differ very much in their yield, from a few l/s to several tens of litres of brackish water.

The results of tracing from the Čiže swallow hole confirm that the general direction of groundwater movement is parallel to the tectonic structures. The tracer injected into the swallow hole appeared only in the Gradole spring both in the case of low (GULIĆ, 1973) and of high waters (MAGDALENIĆ & VAZDAR, 1993).

The hydrogeological function of the flysch deposits is two-fold. In the area of Vižinada, the flysch deposits occur only as a thin cover of isolated small areas, and therefore do not influence groundwater flow. As these deposits form the most elevated parts of the terrain, the precipitation runoff occurs down one or other side of the ridge.

The hydrogeological role of flysch deposits in the area of Novaki Motovunski, the area of Čiže brook and around the Beramski brook is quite different. Impermeable flysch deposits in the area enable the formation of a surface hydrographic network. There are several brooks taking the rain waters down to the contact with the carbonate rocks where water disappears. Precipitation over area of Motovunski Novaki, for example, is captured by the swallow hole west of Škropeti village. Torrential surface waterflows are also controlled by the flysch deposits - marls and sandstones. Flysch deposits also act as a topographic watershed towards the drainage areas of Butoniga accumulation and Pazinčica river.

3.2. UNDERGROUND FLOW-PATHS

An important issue in research of Karst hydrogeology is the tracing of underground connections between swallow holes and springs. Tracing experiments were accompanied by hydrogeological, hydrological and other studies enabling us to determine the underground watersheds, in order to calculate apparent velocities of underground water movement, and to interpret the subsurface structure.

In order to determine the underground flow-paths, several tracing experiments were performed, both within the supposed drainage area and in it's surroundings. At the Čiže swallow hole and in the area of Tinjanska draga multiple tracings were done, using colorimetric (Na-fluoresceine) and isotopic method using tritium (BABIĆ et al., 1968; MAGDALENIĆ & VAZDAR, 1993). Possible locations for tracing experiments are very rare in the Gradole spring drainage area. Although a vast number of pits, fractures and sinkholes are registered, only a small portion of them have either a permanent or intermittent inflow of water. The possibility of water inflow exists only in the southeastern part of the drainage area, the southwestern part, close to the sea, is totally without surface waterflows. The only possibility of tracing in this area would be to transport the water into the pits.

The Čiže swallow hole area is situated in the eastern peripheral part of the drainage area of Gradole spring. The drainage basin discharging towards the swallow hole, has a surface area of approximately 10 km^2, dominated by flysch terrain. The direct surface distance between the Čiže swallow hole and Gradole spring is 14.5 km. A number of tracing experiments at Čiže swallow hole were carried out between 1968 - 1988, under different hydrological conditions (for both the swallow hole and the Gradole spring). The purpose of tracing was to confirm the underground connection between the two so that with a possible increase of the minimal discharge of Gradole spring could be achieved by initiating artificial inflow into the Čiže swallow hole.

All tracing experiments showed that almost 100% of tracers were recorded only at the Gradole spring, regardless of hydrogeological variations (MAGDALENIĆ, 1988[8], "Ruđer Bošković" Institute 1989[9]). For example, connections with the Male Gradole and Očjak springs, situated only 100 m, and 200 m respectively from the main Gradole spring were not confirmed.

Varying underground water conditions, and flow velocities account for differences in the ratio of the underground retention time in dry and rainy seasons. The ratio of apparent velocities in the dry and rainy seasons is 1:9 approximately as deduced from tracing experiments. The time of outflow of a tracer at the spring differs. During high water conditions tracers outflowed at the spring for 10 and 18 days, while in the dry season the outflow lasted for 92 and 93 days.

The possibility of conditioning the discharge of the Gradole spring through the Čiže swallow hole was confirmed by results of tracing of the Čiže swallow hole and by experimental artificial inflow. The cause of the delayed reaction of the spring following the first rainfall is found in the accumulation of water in the emptied underground space. The consequences of this process are small apparent velocities and long-lasting retention of tracer within the subsurface. The results of tracing of the Čiže swallow hole in the dry season are very interesting. Since the tritium emerged 51 days after injection, an apparent velocity of 0.33 cm/s was calculated. This implies that tracer was retained in the underground due to extreme slow water movement between the swallow hole and the spring. More rapid movement of tritium occurs with rising levels of underground water. The overflow of water in the spring was registered 23 days before the tritium appeared, and

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[8] MAGDALENIĆ, A. (1988): Hidrogeološka interpretacija trasiranja ponora Čiže u Istri.- Unpubl. tech. report, Faculty of Mining, Geology and Oil-engineering, Zagreb.

[9] Institute "Ruđer Bošković" (1989): Praćenje dinamike toka podzemne vode od ponora Čiže do izvora V. Gradole prilikom kontinuiranog ulijevanja vode iz akumulacije Butoniga u ponor Čiže.- Unpubl. tech. report, Institute "Ruđer Bošković", Zagreb.

LOCATION DATE TRACER	CONFIRMED CONNECTION WITH SPRINGS	ALTITUDE DIFFERENCE (m)	DISTANCE (km)	DIP ‰	APPARENT FLOW VELOCITY OF GROUND WATER (cm/s)
Swallow hole in the Tinjanska draga (I) 15. IV. 1971. 11 kg of Na-fluoresceine	Gradole	361	17	21.2	0.45
Swallow hole in the Tinjanska draga (II) 6. II.1986. 80 kg Na-of fluoresceine	Gradole Poreč Rovinj Lim Cove	361	17	21.2	0.8
Swallow hole Čiže 26. V. 1968. 100 kg Na-of fluoresceine	Gradole	316	14.5	21.8	0.67
Swallow hole Čiže 16. III. 1976. Tritium	Gradole	316	14.5	21.8	3
Swallow hole Čiže 25. IX. 1987. 1000 Ci of Tritium	Gradole	316	14.5	21.8	0.33
Swallow hole Čiže 14. IX. 1988. 1000 Ci of Tritium	Gradole	316	14.5	21.8	0.57

Table 1 Results of tracings within the Gradole spring drainage area.

there was a pronounced increase in discharge 3 days before the first tritium was recorded.

From the data, it can be concluded that at low water there is no continuity of flow between the Čiže swallow hole and the Gradole spring. In other words, the underground is acting hydraulically as a discontinuous, heterogeneous system.

The commencement of water overflow from the spring and the later appearance of tritium, indicate that the rising of underground water levels together with increasing spring discharge were not only the result of water inflow from the drainage area of the Čiže swallow hole. It is to be assumed that a large amount of recharge results from the catchment area closer to the spring.

The tracings undertaken in the Tinjanska Draga (1971[10], 1986[11]) are very important (MAGDALENIĆ & VAZDAR, 1993). Although the underground connections are not as obvious as in the case of Čiže swallow hole, they nevertheless enable us, together with other geological and hydrogeological data, to determine more precisely the southern borders of the drainage area.

Results of tracings within the Gradole spring drainage area are given in Table 1.

3.3. DIMENSIONS OF THE DRAINAGE AREA AND THE DRAINAGE DIVIDE

The Gradole spring drains the limestone plateau between the river Mirna and Lim Cove. The drainage area is of elongated shape, 17 km long from NW - SE and on average 5 - 6 km wide. Delimitation of the drainage area and the drainage divide is based on geological data, tectonics, structures, morphology, photo geological interpretation of terrain, hydrogeological properties of rocks, the morphological phenomena of karst (sinkholes, pits) and tracing experiment data of underground water movement. The watershed surrounding the Gradole spring is shown on Fig. 2.

The Gradole spring drainage area shares it's northeastern border with the drainage areas of the Krvar and Mufrini brooks, and the Butoniga accumulation. To the east the border is marked by the Beramski brook, Draga and the drainage area of the Pazinčica river. The southern and southwestern border separates the drainage area of the Gradole spring from the drainage areas of Lim Cove and the coastal springs of western Istria. The northeastern watershed between the spring and Vižinada and more distant Karojba is defined as a topographic one, formed in the Vižinada area on flysch deposits, and in the Karojba area on limestones. A topographic border of the drainage area occurs on flysch deposits along a line from Novaki Motovunski around the Čiže swallow hole drainage area to Beramska Vala. The southeastern border of the Gradole spring drainage area in Beramska Vala and along the Draga valley coincides with the streambed in which the swallow holes occur. Tracing experiments proved that the water disappearing into the swallow holes divides flowing either

[10]RALJEVIĆ, B., ČAKARUN, I., KOSTOVIĆ, K., HRELIĆ, Đ., BOŽIČEVIĆ, S. & BABIĆ, Ž. (1971): Regionalna hidrogeološka istraživanja na području Istre.- Unpubl. tech. report, Institute of Geology, Zagreb.

[11]Ina-projekt (1986): Izvještaj o rezultatima hidrogeoloških istražnih radova na području Limske Drage.- Unpubl. tech. report, Ina-projekt, Zagreb.

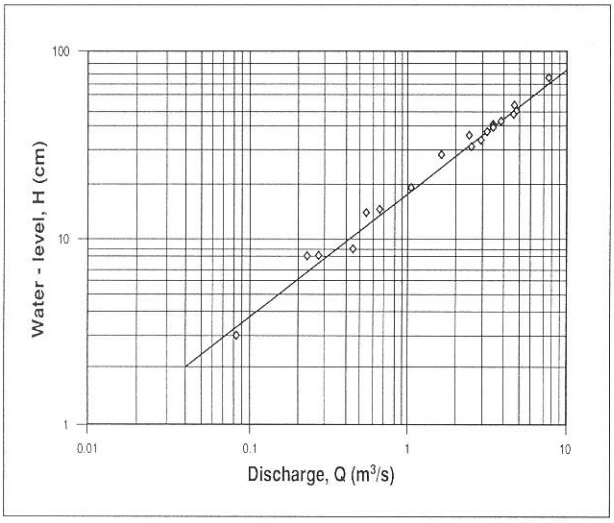

Fig. 6 Gradole spring - discharge curve.

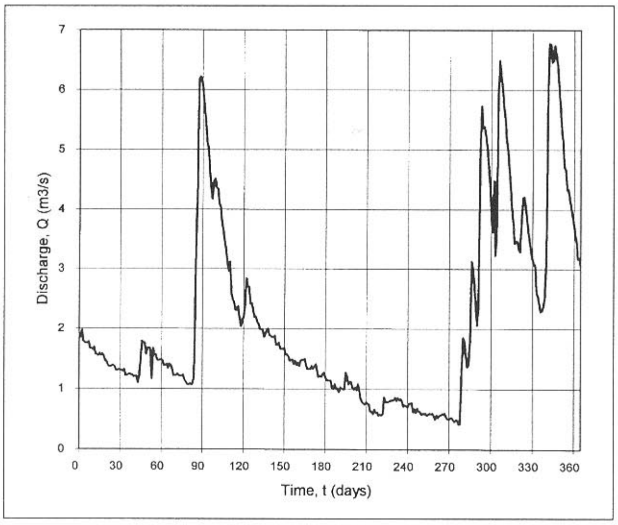

Fig. 7 Characteristic hydrograph of the Gradole spring for 1992.

NW towards the Gradole spring or SW towards the Lim Cove and the springs on the western coast of Istria. The southwestern border of the drainage area, between Tinjanska Draga and the Gradole spring, is interpreted as an underground hydrogeological watershed. The fact that the entire line of the watershed lies in a karst area presents a special problem in determining the border of the drainage area. It is supposed that the watershed is of a zonal type and changes with variations in the hydrogeological condition.

Several pits deeper than 100 m exist in the area although none of them reaches the level of underground water, and there is no surface inflow into the pits. To confirm the interpretation of the underground watershed, a tracing with an artificial inflow of water into a pit would be useful.

Based on the hydrogeological data, the surface of the drainage area of the Gradole spring totals approximately 104 km^2. Of this carbonate rocks make up 85 km^2 and flysch deposits around 19 km^2.

Existing hydrological data were also used to delimit the size of the drainage area. Hydrological analysis (MAGDALENIĆ et al., 1993[12]) considered characteristics of the climate of the surrounding area. A new flow curve was defined, the characteristics of flow determined including; monthly flow, high and low waters, runoff coefficient. From this the calculated size of the drainage area is approximately 113 km^2.

In the course of this study methods and some practical results from BONACCI (1987), BONACCI (1988) and MAGDALENIĆ et at. (1986) have been used. The discharge curve for the period 1987-1991 was defined. It's analytical expression is as follows:

$$Q = 0.01337H^{1.4943}$$

where Q is discharge in m^3/s, and H is water-level in cm (Fig. 6).

The above 5-year data-base includes qualitative measurements of discharge for the Gradole spring, and precipitation for the area of Pazin. After hydrological determination of the surface and borders of the drainage area, on the basis of a hipsometric curve, the mean altitude of the drainage area has been defined as 336 m above sea-level. Average annual rainfall between 1987-1991 was 909.9 mm. Considering the documented fact that in the Gradole spring drainage area precipitation was 5-6% smaller than at the Pazin station (MAGDALENIĆ et al., 1992), it can be concluded that the spring drainage area received an average of 862 mm per annum over the same period.

The runoff coefficients for different estimated surfaces of the drainage area (90-135 km^2) have been determined as 0.701 and 0.548 and diminish with increasing drainage area.

It is known that in Istria the runoff coefficient on flysch is between 0.3 and 0.4 with on average of 0.35. The runoff coefficient of the karst areas is higher, between 0.5 and 0.7 with a mean value of 0.6. The surface of the drainage area defined by the hydrogeological exploration is partly in flysch (18%) but mostly in carbonate rocks (82%).

Out of this, the mean value of runoff coefficient of the whole drainage area is:

$$\alpha_{mean} = 0.35 \times 18\% + 0.6 \times 82\% = 0.555$$

Acquired value of α_{mean} is in accordance with the surface of the drainage area of A=113 km^2.

The difference in the size of the calculated drainage area can be attributed. Partly to the imprecise determination of hydrogeological borders in the karst area, and also to human error or unreliability of hydrological data.

[12] MAGDALENIĆ, A., BONACCI, O., VAZDAR, T & HLEVNJAK, B. (1993): Sliv izvora Gradole U Istri. Zone sanitarne zaštite. Hidrogeološka i hidrološka studija.- Unpubl. tech. report, Faculty of Mining, Geology and Oil-engineering, Zagreb.

3.4. GRADOLE SPRING

The Gradole spring is situated some 9.5 km upstream of the mouth of the river Mirna. It is situated on the edge of the valley, at the base of a vertical rock wall. The spring originally morphologically resembled a small oval lake, 8 x 16 m, with water erupting from a crevasse in the lake bed. During preparations for building an intake structure, several minor caves were found. According to BOŽIČEVIĆ (1985) the caverns resemble the remains of once integer morphological system connected to the creation of the karst spring Gradole.

The vertical cliff of horizontally layered Cretaceous limestones is the edge of a spatious limestone plateau in the hinterland of the spring.

The regime of the spring is discussed by GULIĆ (1973), who concluded that, during low waters, the reduction of water-level at the spring results in an increase of springflow, whilst in the high-water period, at the time of maximal flow, the reduction of water-level has practically no influence on the springflow. Figure 7 shows the characteristic hydrograph of Gradole spring for the year 1992. The emptying of the underground retention is slowed down by elevating the overflow weir, and thereby the minimal springflow is artificially increased. Tracing results indicate the possibility of regulating the overflow, as the tracer appeared only at Gradole spring both in the case of low and high waters, and the existence of side flows wasn't observed. Springflow depends on both the quantity and intensity of rainfall. Similar quantities of rainfall do not necessarily equally affect the spring. In the dry season, rainfall is firstly accumulated in vacant underground storage space, prior to the influence of rainfall on the spring becoming observable. The time of reaction of the spring with respect to the events on the surface ranges between 24 and 72 hours or more.

Observations of the water turbidity on the spring are very interesting as the turbidity is a function of rainfall; both it's intensity and duration. Turbid water enters the underground as run-off and previously deposited underground sediment is disturbed simultaneously. After rainfall of a certain threshold intensity (usually $\geq$30 mm), the turbidity of water appears instantly.

The development of turbidity on the spring is characterized by four phases (GULIĆ & ROGLIĆ, 1980[9]):

- period of turbidity increase from the first appearance till the culmination (24 to 72 hours)
- stable maximal turbidity for 3 to 5 days
- decrease of turbidity below 100° within 3 to 4 days
- period of disappearing of turbidity lasting between 15 and 30 days.

The minimal springflow averages 500 to 600 l/s, the maximum rising to 15 m^3/s, a ratio is varying up to 1:20. This is fairly uniform discharge behaviour in the karst area.

The underground connection established between the Čiže swallow hole and the Gradole spring indicates the possibility of artificial augmentation of springflow by bringing additional water in the swallow hole. The experiment (MAGDALENIĆ, 1988[8]) showed that introducing water to the Čiže swallow hole increased the discharge of the Gradole spring. A total of 623,682 m^3 of water from the Butoniga accumulation was diverted to the swallow hole, a procedure repeated in the summer season of 1990. There was no further introduction of water to the Čiže swallow hole in the years that followed.

In the close vicinity of the Gradole spring two more intermittent springs were found. The Male Gradole spring is 100 m upstream from the Gradole spring, while the Očjak spring occurs 250 m downstream. During repeated tracing of the Čiže swallow hole, the tracer did not appear at these two springs.

4. CONCLUSION

The data presented in this paper are an example of an interdisciplinary approach to problems in karst areas. The surface and spatial position of the drainage area were defined by the analysis of geological, structural, morphological, and hydrogeological data. The drainage area covers 104 km^2 (some 85 km^2 in karst, 19 km^2 in flysch area). The hydrological analysis of existing data defined the discharge area of the spring with a size of 113 km^2.

The tracing experiments are spatially unequally distributed. Tracing of the Čiže swallow hole was done on 4 occasions, while no tracing was carried out along the southwestern border of the drainage area, between Tinjanska Draga and the spring. This surely influences the accuracy of defining the watershed in this totally karst area. The spelaeological exploration failed to register the level of underground water in any of the pits.

The karst area is without any surface waterflows, while in the flysch area the hydrographic network of intermittent flow is developed. There are no real barriers to underground water movement within the carbonate rocks. The direction of underground flow is nevertheless under the influence of structural elements, the position of layers, the appearance of the strata-thin layers, occurrences of less permeable rocks - dolomites, fissured and marly limestones.

The Gradole spring belongs to the group of karst springs of rising type. It never runs dry. The ratio of minimal and maximal discharge varies on average from 1:15 to 1:20 or more. This is regarded as a fairly uniform springflow, essential for the usage of a spring in the water supply. There are favourable hydrogeological conditions for artificial recharge of the aquifer system by diverting water from the Butoniga accumulation to the Čiže swallow hole. A problem of the use of the Gradole spring is not only the quantity, but also the preservation of the water quality. With respect of the fact that more than 80% of the drainage area is made of permeable carbonate rocks, the risk of groundwater contamination is very high.

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